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BIODIVERSITY IN ENCLOSED SEAS

Artificial habitats and the restoration of degraded marine ecosystems and fisheries

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Abstract Artificial habitats in marine ecosystems are employed on a limited basis to restore degraded natural habitats and fisheries, and more extensively for a broader variety of purposes including biological conservation and enhancement as well as social and economic development. Included in the aims of human-made habitats classified as artificial reefs are: Aquaculture/marine ranching; promotion of biodiversity; mitigation of environmental damage; enhancement of recreational scuba diving; eco-tourism development; expansion of recreational fishing; artisanal and commercial fisheries production; protection of benthic habitats against illegal trawling; and research. Structures often are fabricated according to anticipated physical influences or life history requirements of individual species. For example, many of the world's largest reefs have been deployed as part of a national fisheries program in Japan, where large steel and concrete frameworks have been carefully designed to withstand strong ocean currents. In addition, the differing ecological needs of porgy and sea bass for shelter guided the design of the Box Reef in Korea as a device to enhance productivity of marine ranching. The effect of these and other structures on fisheries catch is positive. But caution must be exercised to avoid using reefs simply as fishing devices to heavily exploit species attracted to them. No worldwide database for artificial habitats exists. The challenge to any ecological restoration effort is to define the condition or possibly even the historic baseline to which the system will be restored; in other words, to answer the question: "Restoration to what?" Examples of aquatic ecosystem restoration from Hong Kong (fisheries), the Pacific Ocean (kelp beds), Chesapeake Bay (oysters) and the Atlantic Ocean (coral reefs) are discussed. The degree to which these four situations consider or can approach a baseline is indicated and compared (e.g., four plants per 100 m^2 are proposed in one project). Measurement of performance is a key factor in restoration planning. These situations also are considered for the ecosystem and fishery contexts in which they are conducted. All use ecological data as a basis for physical design of restoration structures. The use of experimental, pilot and modeling practices is indicated. A context for the young field of marine restoration is provided by reviewing major factors in ecosystem degradation, such as high stress on 70% of commercially valuable fishes worldwide. Examples of habitat disruption include an

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extensive hypoxic/anoxic zone in the Gulf of Mexico and nutrient and contaminant burdens in the North Sea. Principles of ecological restoration are summarized, from planning through to evaluation. Alternate approaches to facilitate ecological recovery include land-use and ecosystem management and determining levels of human population, consumption and pollution.

Keywords Artificial habitats · Reefs · Estuaries · Ocean · Restoration

Introduction

Degradation of coastal and ocean habitats, ecosystems and fisheries is a global concern. It motivated the content of the 2004 World Fisheries Congress, for example, where the issues of serial depletion of fisheries by size, area and trophic level, and impairment and destruction of ecological system structure and function were quantified. Examples of overharvest come from all seas, such as the collection of fewer and smaller sea horses and damage to their coral reef habitat in the Indo-Pacific to supply the world aquarium trade and certain medicinal markets. According to the Food and Agriculture Organization of the United Nations (FAO), 18% of major marine fish stocks or species groups are reported as overexploited (FAO, 2002). One of the voices calling attention to this condition is Daniel Pauly, keynote speaker at the World Fisheries Congress, whose ''Sea Around Us'' project quantifies the consequence of ''fishing down the food chain'' as top carnivores are decimated by fishing and landings shift to emphasize lower trophic levels (Pauly et al., 1998).

Aquatic habitats are characterized by impairments such as dredging, draining and damming of riverine floodplains and destruction of coastal wetlands. Worldwide, one-third of the world's coasts are at ''high potential risk of degradation,'' according to the United Nations. Along the seacoasts of Europe, degradation may take the form of seagrass bed destruction, eutrophication or fishery overharvest. In the North Sea, for example, the impacts of fisheries activities, trace organic contaminants and nutrients are classified as ''First Priority'' by the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Commission, 2000) of the Oslo and Paris Commissions. Despite improvements for certain pollutants/disturbances, the OSPAR Quality Status Report raises concerns for these three stressors and future loss or disturbance of ''many sensitive habitats'' in coastal areas.

As one type of response, when appropriate, ecological restoration aims to return a system to some level of pre-degraded state. One intent is ''to establish a functional ecosystem of a designated type that contains sufficient biodiversity to continue its maturation by natural processes and to evolve over longer time spans in response to changing environmental conditions'' (Clewell et al., 2000).

This paper addresses the role of artificial reef habitats in restoration of degraded marine systems. It first examines the overall context for ecological restoration in both terrestrial and aquatic environments, provides definitions for various objectives and practices, and directs the reader to relevant information resources. Some trends and guiding principles (e.g., establishment of measurable objectives) relevant generally to restoration and specifically to artificial marine habitat technology are indicated. This information is presented to assist the multiple disciplines and interests concerned with the use of artificial habitats to better assess their relevance and role in ecosystem and fishery science and management, and in return aid the practitioners. The proper role of artificial habitats in aquatic systems continues as an item of debate in scientific circles. Evidence for their role is presented in a brief analysis of four situations concerning restoration of kelp, coral reefs, oysters and fish populations.

The information presented complements the second theme of the 39th European Marine Biology Symposium, on ''Artificial Habitats and Restoration of Degraded Systems,'' which contained 17 oral and 17 poster contributions. The approach to preparation of this paper was to review a predetermined number of organizations (10), journals (5), articles (ca. 20) and websites (15) representative of effort in this field in Asia, Africa, Australia and the Americas, and to a lesser degree in Europe.

Context for marine restoration

A brief indication of the nature of ecosystem degradation (including causes and effects) and restoration (practices and results) is given here. Some overall trends, definitions and efforts are noted. Coastal restoration is a growing endeavor, albeit limited. One example is the initiation of over 650 ''community-based restoration projects'' sites in the United States since 1996 under the auspices of the NOAA Restoration Center, established in the U.S. National Marine Fisheries Service, Office of Habitat Conservation (NOAA Restoration Center, 2004). This program relies heavily on local community participation, including volunteer efforts by citizens. Yet, as noted by Beck et al. (2003, p. 10), ''our ability to restore ecosystems such as marshes and seagrass meadows is quite limited.''

Definitions

Ecological Restoration is the ''process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed,'' according to the Society for Ecological Restoration (SER, 2004, p. 2). This source further identifies ''deviations from the normal or desired state of an intact ecosystem'' to include degradation, damage, destruction and transformation, recognized as overlapping and sometimes unclear terms that describe the degree of alteration. Degradation is defined as pertaining to ''subtle or gradual changes that reduce ecological integrity and health.'' Recovery or restoration of an ecosystem is achieved when ''it contains sufficient biotic and abiotic resources to continue its development without further assistance or subsidy'' (SER, 2004, p. 3). Moreover, it is intentional, and ''initiates or accelerates an ecological pathway through time towards a reference ecosystem or a target ecosystem condition'' (CEM [Commission on Ecosystem Management, IUCN/The World Conservation Union, Gland, Switzerland], unpublished draft, Ecological Restoration).

According to the NOAA Restoration Center, restoration is ''the process of reestablishing a self-sustaining habitat that closely resembles a natural condition in terms of structure and function...These habitats support fish and wildlife, and human uses such as swimming, diving, boating, and recreational and commercial fishing. Restoration usually does not focus on a single species but strives to replicate the original natural system to support numerous species. The goal is to expedite natural processes in rebuilding a healthy, functioning natural ecosystem that works like it did before it was polluted or destroyed.''

Measures of restoration or recovery will determine, for example, progress in ''returning a polluted or degraded environment as closely as possible to a successful, self-sustaining ecosystem with both clean water and healthy habitats'' (NOAA Restoration Center). Thus, ''An ecosystem is considered to be fully restored when it contains sufficient biotic and abiotic resources to sustain its structure, ecological processes and functions with minimal assistance or subsidy. It will demonstrate resilience to normal ranges of environmental stress and disturbance. It will interact with contiguous ecosystems in terms of biotic and abiotic flows and social and economic interactions. It will support, as appropriate, local social and economic activities. Such a state, however, is rarely achieved, even in the long-run. Nevertheless, significant environmental and social benefits can be realized even in the earliest stages of restoration'' (CEM).

In the preceding definitions, both the terms ecosystem and habitat are used. ''Habitat refers to the dwelling place of an organism or community that provides the requisite conditions for its life processes'' (SER, 2004, p. 4). In turn, habitat is part of the ecosystem, defined by the Ecological Society of America (Beck et al., 2003, p. 3) as ''characteristic assemblages of plants and animals and the physical environment they inhabit (e.g., marshes or oyster reefs). The term habitat refers to the area used by a species.'' This definition extends to include modifiers that identify ''particular habitats used by an animal. For example, the blue crab...has a seagrass habitat and a marsh habitat...portions of seagrass and marsh ecosystems, respectively.''

Extent

Habitat and ecosystem degradation is documented from the local to the global level. Among terrestrial organisms butterfly and songbird life cycles in North America are threatened by destruction of critical habitat along migration routes (Nature Conservancy; website: http://nature.org). Two hundred years ago the ‘‘Corps of Discovery’’ led by the so-called Lewis and Clark Expedition of 1804–1805 encountered herds of bison (buffalo) that were part of a species of 70,000,000 individuals. By 1881 the number of bison was reduced to 350, and in modern times it has been restored to 325,000, a small fraction of the original abundance.

‘‘The state of the world’s fisheries is poor, and continues to degenerate. 70% of commercially valuable fisheries have collapsed or are overfished and en route to collapse. The biggest threats to fishery health worldwide include: Pollution from land-based sources; habitat alteration and destruction; non-sustainable and destructive fishing techniques; global climate change. The deteriorating state of the world’s fisheries has social, economic and ecological implications: commercial and artisanal fishing is a source of income and a way of life for coastal populations, seafood is an important source of food and protein for the global population and demand for it is rising, and the depletion in stocks of commercially targeted fish, as well as the depletion of marine species that are incidentally caught (by-catch) with targeted species, has altered and unbalanced the food web of the world’s oceans. The consequences of this destabilization are ecologically complex and only beginning to be understood.’’ (International Oceanographic Commission; website: http://ioc.unesco.org/iocweb/ecosystems.php).

In marine systems, all major environments have been affected. Causes of degradation include land-based wastes including nutrients and toxic chemicals. Impacts include ‘‘dead zones’’ such as an area of as large as 20,000 square kilometers (Turner et al., 2004) in the Gulf of Mexico (an area about half the size of Switzerland). The United Nations Atlas of Fisheries states that ‘‘one of the greatest long-term threats to the viability of commercial and recreational fisheries is the continuing loss of marine, estuarine and other aquatic habitats.’’ Further, ‘‘pathogens, toxic waste and toxins from Harmful Aquatic Blooms (HABs) have a major impact on fisheries, not only from the impact on human health, but from the closure of fisheries in contaminated areas. The losses in areas which are permanently polluted is hard to measure, however during periods of HABs, the economic losses have been calculated for a number of locations. A red tide in Hong Kong in 1998 caused losses of US$32 million from the closure of fish farms, whilst an algal bloom in Korea in 1991–1992 was estimated to cost US$133 million. Solid waste also has an impact on fisheries. The constant trawling and dredging operations have significant impact on the sea floor. It is similar to farming in that areas are cleared of rocks and obstacles, the terrain is leveled, and each succeeding year gear passes easier over the bottom. At the same time though, just as fields of wheat replace forests, trawlable bottom replaces coral heads and rock piles. The ecology of plants and animals is greatly changed.’’ (United Nations Atlas of the Oceans; website: http://www.oceansatlas.org.)

Responses

The rationales for restoration include maintaining food supply, maintaining biodiversity, protecting nature, protecting human health, creating jobs and preserving ways of life (NOAA Restoration Center). Indigenous peoples and industrialized nations alike have responded to the growing loss of marine habitat function and structure. As reported by A. Vincent at the 2004 World Fisheries Congress, residents of artisanal fishing communities in the Philippines are keenly aware of options for fisheries restoration and adopting sustainable conservation practices concerning seahorses (personal communication; website: http://www.projectseahorse.org/). Similarly, in the United States local initiative has been responsible for coastal restoration nationwide, in part facilitated by programs such as the NOAA Restoration Center which seeks to study ecosystem structure, function and recovery, and develop restoration methods, success criteria and monitoring practices.

Efforts to develop and exchange information on a global basis include the development of restoration workshops and guidelines by the Commission on Ecosystem Management (CEM) of IUCN/The World Conservation Union. The mission of the Society for Ecological Restoration (SER) is "to promote ecological restoration as a means of sustaining the diversity of life on Earth and reestablishing an ecologically healthy relationship between nature and culture." It has published a primer on the subject, produces two journals and conducts an annual conference, for which it creates a lasting record on its website. Its membership of 2,300 is engaged in committees and working groups.

Principles and performance

Ecosystem restoration is young. Science-based policies and guidelines for effective restoration practices, including planning and evaluation, have been formulated in recent years. Among the international and national policies and laws concerning ecosystem restoration, the European Environment Agency (EEA) Strategy for 2004–2008 offers one approach to establishing a foundation for restoration and recovery of ecosystems. As part of its sixth environment action programme, the EEA lists as priorities halting biodiversity loss, assessment of marine ecosystem health and support for implementation of the EU marine strategy (EEA, 2003).

In North America, a partnership between the Estuarine Research Federation and Restore America's Estuaries produced a document entitled "Principles of Estuarine Habitat Restoration" (Waters, 1999) organized into four categories: (1) Context (four principles—preservation, stewardship, increasing scale, public participation); (2) Planning (two principles—ecosystem perspective, stakeholders/science); (3) Design (four principles—goals long-term and measurable, success criteria linked to reference habitats, impacts, monitoring); (4) Implementation (four principles—ecological engineering, adaptive management, protection, public access).

Among the science-based practices promulgated by organizations mentioned in this paper, and others, Clewell et al. (2000) identify and briefly describe 51 guidelines for ecological restoration, which address planning, organization, implementation and evaluation phases (Table 1). The extensive list of tasks would be especially useful to organizations just beginning to conceptualize restoration efforts in marine ecosystems.

The absolute need for establishment of measurable objectives in ecosystem restoration is emphasized by numerous authors and organizations. For example, two questions posed by Proffitt (2004) are: "What are appropriate time frames and measures for evaluating success? What do we establish as target restoration conditions?" Beck et al. (2003) note a consistent lack of effort to monitor restoration in nearshore ecosystems, thereby compromising efforts to gauge success or failure. Moreover, these authors encourage comprehensive evaluation to document returns of species, communities, and ecological functions.

Finally, a context for habitat restoration may be framed by asking: "Restoration to what?" It is essential that a "baseline" condition be defined by ecosystem, fishery and habitat scientists and managers, and other informed stakeholders, as a guide for design of an environmental restoration project and for its evaluation. This definition should be established prior to implementation. "Natural" conditions presumed for a given coastal system likely represent a "shifted" baseline given the ubiquity of historical overexploitation (Jackson, 2001). An example derives from what is possibly the largest restoration ever attempted in the world, the Greater Everglades Ecosystem Restoration, with costs estimated at U.S. $8 billion (USACOE, 1999) over 20 years. This program aims to return estuaries in South Florida, USA to earlier conditions by restoring natural quantities, qualities, timing, and distribution of freshwater inputs altered by drainage and flood control systems implemented over the past 50 years. Efforts include filling straightened channels of a river and restoring its original meandering course. However, elevation changes over the landscape due to soil oxidation and subsidence in drained wetlands make the historical condition of freshwater flow impossible to restore. Also, a substantial portion of the system is now in urban development.

Table 1 Excerpts[a]: Society for Ecological Restoration International ''Guidelines for Ecological Restoration.'' (Note: Most annotations for the 51 steps listed are not reproduced here.)

The mission of every ecological restoration project is to reestablish a functional ecosystem of a designated type that contains sufficient biodiversity to continue its maturation by natural processes and to evolve over longer time spans in response to changing environmental conditions.

(A). CONCEPTUAL PLANNING (Reasons why restoration is needed, general strategy for conducting it.)

1. Identify the project site location and its boundaries.
2. Identify ownership.
3. Identify the need for restoration. (Tell what happened at the site that warrants restoration. State the intended benefits of restoration.)
4. Identify the kind of ecosystem to be restored and the type of restoration project.
5. Identify restoration goals, if any, that pertain to social and cultural values.
6. Identify physical site conditions in need of repair.
7. Identify stressors in need of regulation or re-initiation.
8. Identify biotic interventions that are needed.
9. Identify landscape restrictions, present and future.
10. Identify project-funding sources.
11. Identify labor sources and equipment needs.
12. Identify biotic resource needs.
13. Identify the need for securing permits required by government agencies.
14. Identify permit specifications, deed restrictions, and other legal constraints.
15. Identify project duration.
16. Identify strategies for long-term protection and management.

(B). PRELIMINARY TASKS (These tasks form the foundation for well-conceived restoration designs and programs.)

17. Appoint a restoration ecologist.
18. Appoint the restoration team.
19. Prepare a budget to accommodate the completion of preliminary tasks.
20. Document existing project site conditions and describe the biota. (Project evaluation depends in part upon being able to contrast the project site before and after restoration.)
21. Document the project site history that led to the need for restoration.
22. Conduct pre-project monitoring as needed. (Obtain baseline measurements.)
23. Gather baseline ecological information and conceptualize a reference ecosystem from it upon which the restoration will be modeled and evaluated.
24. Gather pertinent autecological information for key species.
25. Conduct investigations as needed to assess the effectiveness of restoration methods.
26. Decide if ecosystem goals are realistic or if they need modification.
27. Prepare a list of objectives designed to achieve restoration goals. (Objectives are the specific activities to be undertaken for the satisfaction of proper goals. Objectives are explicit, measurable, and have a designated time element.)
28. Secure permits required by regulatory and zoning authorities.
29. Establish liaison with other interested governmental agencies.
30. Establish liaison with the public and publicize the project.
31. Arrange for public participation in project planning and implementation.
32. Install roads and other infrastructure needed to facilitate project implementation.
33. Engage and train personnel who will supervise and conduct project installation tasks.

(C). INSTALLATION PLANNING (The care and thoroughness with which installation planning is conducted will be reflected by how aptly project objectives are realized.)

34. Describe the interventions that will be implemented to attain each objective.
35. State how much of the restoration can be accomplished passively.
36. Prepare performance standards and monitoring protocols to measure the attainment of each objective. (A performance standard [also called a design criterion] provides evidence on whether or not an objective has been attained. This evidence is gathered by monitoring. It is essential that performance standards and monitoring protocols be selected prior to any project installation activity.)
37. Schedule the tasks needed to fulfill each objective.
38. Procure equipment, supplies, and biotic resources.
39. Prepare a budget for installation tasks, maintenance events, and contingencies.

(D). INSTALLATION TASKS

40 Mark boundaries and secure the project area.

41. Install monitoring features.
42. Implement restoration of objectives. (Restoration tasks identified in Guideline #34.)

Table 1 continued

(E). POST-INSTALLATION TASKS

43. Protect the project site against vandals and herbivory.
44. Perform post-implementation maintenance.
45. Reconnoiter the project site regularly to identify needs for mid-course corrections.
46. Perform monitoring as required to document the attainment of performance standards.
47. Implement adaptive management procedures as needed.

(F). EVALUATION

48. Assess monitoring data to determine if performance standards are being met.
49. Describe aspects of the restored ecosystem that are not covered by monitoring data.
50. Determine if project goals were met, including those for social and cultural values. (Based on monitoring data and other documentation [Guidelines #46, #49], evaluate the restoration with respect to its project goals. These will include the primary goal to restore a functional ecosystem that emulates the reference ecosystem at a comparable ecological age [Guideline #4]).
51. Publish an account of the restoration project and otherwise publicize it. Publicity and documentation should be incorporated into every restoration project for the following reasons: Published accountings are fundamental for instituting the long-term protection and stewardship of a completed project site. Policy makers and the public need to be apprised of the fiscal and resource costs, so that future restoration projects can be planned and budgeted appropriately. Restoration ecologists improve their craft by becoming familiar with how restoration objectives were accomplished.

[a] Source: Clewell et al. (2000)

Artificial habitats in marine restoration

Over centuries the role of artificial habitats in aquatic environments has expanded from a relatively simple set of procedures applied at a small-scale and using natural materials designed to enhance success of local fishing harvest, to a more involved technology used more broadly in environmental management. From documented origins in Japan, these practices are employed in scores of nations in temperate and tropical areas. The historical goal of increased food production continues in both artisanal fisheries (e.g., India) and commercial fisheries (e.g., Taiwan) settings. In a more controlled situation, artificial reefs are used as a physical basis for aquaculture (e.g., Italy), which in its more complicated aspects is known as marine ranching due to the use of complementary manipulations such as introduction of hatchery-reared fingerlings to augment recruitment (e.g., Korea). In the last 10 years, another historical goal—enhancement of recreational fishing (e.g., Australia)—has been augmented by use of artificial habitats to promote recreational diving (e.g., Canada) and eco-tourism (e.g., Bahamas) and conservation of biodiversity (e.g., Monaco). It is likely that ecosystem restoration is the newest and least widespread application for artificial reefs.

The definition of an artificial reef as ‘‘a submerged structure placed on the seafloor deliberately, to mimic some characteristics of a natural reef’’ appears in the OSPAR Guidelines on Artificial Reefs in Relation to Living Marine Resources (OSPAR, 1999), having been adopted from the definition of the European Artificial Reef Research Network. This material derives from the Convention for the Protection of the Marine Environment of the North-East Atlantic, presented at the Ministerial Meeting of the Oslo and Paris Commissions in 1992. Among a diversity of applied and conservation purposes for artificial reefs, restoration of marine areas (including ‘‘regeneration of marine habitats’’) is identified. Considerations in the OSPAR Guidelines include: definition and purpose for artificial reefs; justification and impacts; materials, design and placement; monitoring to verify fulfillment of objectives and degree of benefit; and the role of pilot studies and experiments.

Principally due to a series of international and more recent regional and national scientific conferences on artificial habitats, a body of technical literature has developed for this field in the last 20 years. This material includes description of the uses of reefs noted above. The larger international meetings attracted as many as 350 individuals; programs in 1983, 1987, 1989, 1995 and 1999 resulted in five published volumes. Regional and national meetings, meanwhile, have occurred in Europe (Jensen et al., 2000), Korea, Canada, Brazil and elsewhere. Of 56 papers in the *ICES Journal of Marine Science* issue devoted to a proceedings of the Seventh International Conference on Artificial Reefs and Related Aquatic Habitats, 29 were produced by European authors (ICES, 2002). Over the approximate 20-year history of the development of this research literature, an initial body of descriptive work has been augmented by results from experimental and hypothesis-driven research designed for understanding and predicting ecological behavior of reefs.

The following four case studies are presented as a guide to current and emerging considerations for habitat restoration. The practices addressed in this paper involve purposeful placement of either human-made or natural materials in a benthic marine ecosystem, generally on the coastal shelf or in an estuary, with a goal of modifying ecological structure and function. These examples from Atlantic, Indian and Pacific Ocean biogeographic regions address restoration of plant habitats, coral reefs, bivalve mollusk systems and fisheries stocks. Restoration is just one tool available for the response to system degradation. Clearly, reduction of pollution, limits to fishing, regulation of coastal development, and dealing with both human population growth and consumption of natural resources all must be considered for application to aspects of the situations considered in this paper.

Kelp bed mitigation and restoration

A large kelp (*Macrocystis pyrifera* Linnaeus) bed is being created as mitigation for habitats destroyed in the coastal Pacific Ocean by the operations of the San Onofre Nuclear Generating Station in southern California, USA (Reed et al., 2002). The owners of the electrical power plant were mandated to create 61 ha (150 acres) of new kelp bed habitat. Placement of artificial reefs is part of this project (Fig. 1). Work began with a moderate sized 8.9 ha (22 acres) pilot project costing U.S. $4 to 6 million, to gain assurance that an appropriate design for the full-scale reef would yield the habitat characteristics and functions legally required by the mitigation permit.

Fig. 1 Deployment of material for kelp mitigation reefs is typical of worldwide practices that use barges for transportation and staging. (Photograph from Southern California Edison.)

Experimental reefs with different substrate characteristics (quarry rock vs. concrete and different coverage of hard substrate vs. sand) are undergoing extensive evaluation to determine the degree of habitat improvement for fishes and benthic communities provided. Recruitment and growth of giant kelp, or survival and growth of transplants, onto the artificial reef structure is a principal concern. Certain performance standards are in terms of an absolute historic baseline: the total amount of kelp that was lost, ultimately 61 ha, at a density of 4 adult plants/100 m^2 (Reed, 2002). Others are stated relative to current status of other similar habitats in the area. For example, fish assemblage, recruitment, and production should be ‘‘similar to natural reefs in the region’’ (Reed et al., 2002). Initial monitoring indicates that both kelp density, and fish recruitment as measured by young-of-year juvenile fish density, compare favorably with natural reference reefs. Deysher et al. (2002) conclude that a low relief structure with moderate sand cover between reefs has the best chance for success.

Coral reefs in site-specific situations

It is estimated that shallow coral reefs worldwide occupy some 284,300 square kilometers, less than 1.2% of the world's continental shelf area (Spalding et al., 2001). Indonesia possesses the largest amount of coral reef, followed by Australia and the Philippines. Reefs worldwide are degraded by over-fishing, coastal development, the introduction of sewage, fertilizer and sediment, and more recently by tsunami, with an estimated 27% lost.

The 1999 International Conference on Scientific Aspects of Coral Reef Assessment, Monitoring, and Restoration convened scientists and stakeholders from all oceans with 13 of 51 published papers addressing restoration, a field in its infancy but rooted in growing scientific understanding of coral reproduction, recruitment and physiology (National Coral Reef Institute, 2001). According to the United States Coral Reef Task Force (2000) the majority of experience for restoration is based on repair of vessel grounding sites, through creation of habitat and transplantation.

Coral reef damage results from ship groundings and fishing gear damage. In the Experimental Oculina Research Reserve in the Atlantic off Florida, USA the ivory tree coral, *Oculina*, was degraded by commercial and recreational fishing. Extensive areas were reduced to rubble by trawling or dredging. Reef fish populations were low. Restoration was attempted with concrete modules, cement blocks (Fig. 2) and PVC piping on first an experimental basis (1996–1999) and then more extensively (2000–2001) (Koenig, 2001). Live *Oculina varicosa* (Lesueur) colonies, approximately 15 cm (6'') in diameter, and small *Oculina* fragments were attached to each reef ball with concrete and cable ties. Also, 450 patio stones with an *Oculina* fragment attached to the top of a 30 cm (1'') PVC pipe were deployed. Koenig (2001) reported that high rates of coral transplant survival in pilot studies led to a larger restoration effort by the U.S. National Marine Fisheries Service, which led to an increase in numbers of individuals of groupers (Serranidae) and possible spawning and nursery functions for this habitat.

In 1993 a United States submarine ran aground on a coral reef off southeast Florida (Jaap, 2000). Physical damage to the reef substrate covered 2,310 m^2, with 1,205 m^2 totally destroyed. In 1997, the State of Florida was awarded a settlement of U.S. $750,000 by the Federal government for environmental damages caused by the submarine grounding. In experiments using artificial reefs, scientists are examining three restoration strategies: (1) enhancing coral recruitment through the use of coral larval attractants, (2) the effect of reef structure on fish assemblages, and (3) the interaction between fish assemblages and coral recruitment and survival (R. Dodge, Nova Southeastern University, personal communication). This is a good example of the advantages offered by artificial reefs for manipulation of ocean habitats for experimentation.

Oysters in ecosystem context

The Chesapeake Bay on the Atlantic coast of the United States represents a system with a drastically shifted baseline. Declines in oyster abundance and habitat and loss of seagrasses have

Fig. 2 Concrete building blocks are common in experimental manipulations of marine benthic habitat, such as in the study of restoring *Oculina* reefs. (Photograph from NOAA Restoration Center Image Catalog, image r0022703, U.S. National Oceanic and Atmospheric Administration [NOAA].)

been co-incident with increased turbidity, eutrophication and anoxia. As early as 1881, oyster (*Crassostrea virginica* Gmelin) beds had reduced structure, increased amounts of sand and mud, and were composed of 97% broken shell and debris as compared with 30% for unfished beds (Wilson, 1881, cited in Kennedy & Breisch, 1981). Oyster harvest in Chesapeake Bay has declined from its peak in 1874 (14 million bushels, about 50 million ton) to less than half a million bushels (1.8 million ton) in recent years. The current stock is approximately 2% of the historic baseline.

Because oysters are filter feeders, there has come to be wider acceptance that their loss may have been a factor in the decline of water quality (Coen & Luckenbach, 2000), and that restoration of habitat may depend on maintaining a certain biomass of filter feeders in the system. Traditional oyster habitat restoration approaches focused narrowly on providing low artificial shell reefs to attain fisheries goals, i.e., increasing harvestable oysters, but did not meet with success (Lenihan, 1999; Coen & Luckenbach, 2000).

A more recent scientific consensus (e.g., Coen & Luckenbach, 2000) is emerging that, for artificial oyster reefs to constitute effective habitat improvement, they need to be (1) taller in order to provide more structurally complex habitat and a potential refuge from bottom anoxia events and (2) protected from harvesting in order to provide for persistence of the reef structure and the maintenance of sufficient oyster biomass both for filtering and for reproductive capacity (Coen & Luckenbach, 2000). Models have predicted that maintaining an average oyster biomass of 25 g/m^2 would reduce turbidity by an order of magnitude. This would greatly increase the amount of light reaching the bottom and thereby expand the suitable area for seagrasses habitat (Newell et al., 2003). A small number of limited pilot restoration efforts are beginning.

Fisheries populations

The fourth case study of structural/physical responses to habitat and fishery degradation includes the most emphasis on simulation modeling of ecosystems, fishing and policy, and is the newest. In Hong Kong, China, high trawling effort during the last quarter of the 20th century produced declining catch, high fishing mortality, greater relative capture of low-value short-lived species, and virtual elimination of longer lived demersal species of higher value (Pitcher et al., 2002). After a peak fishery harvest of over 240,000 tons in 1989, catch in 1998 was under 145,000 tons (Wilson et al., 2002). In response a multi-faceted approach including fishing licenses, protected areas, and restoration and enhancement of habitats was proposed; a five-year Artificial Reef Programme started in 1996, funded at U.S. $13,000,000 (Wilson et al., 2002). These latter authors described preliminary results including juvenile fish recruitment for species of Sparidae and Lutjanidae, residence of adult Serranidae, and increased catch of small-scale fisheries for bream (Sparidae).

Habitat restoration structures included deployed vessels (including along park boundaries to prevent trawling), rock, tire units and concrete units (28,000 m^3 total) (Fig. 3) in two marine parks. This was according to a voluntary no-fishing arrangement made possible by placement of additional artificial reefs for fishing in open mud areas. An area of 10% of Hong Kong waters has been set aside as a "Fisheries Protection Area." According to predictions by Pitcher et al. (2001) the value of the fishery would increase by over 50% if 10–20% of waters were managed on a no-take basis.

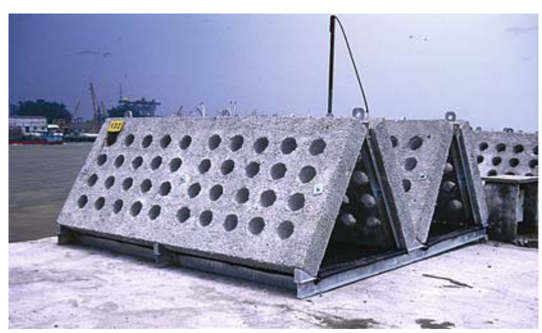

Fig. 3 The trend in construction of artificial reefs is for increasing use of designed modules, such as this concrete structure deployed in Hong Kong. Dimensions are $4.0 \times 4.4 \times 1.6$ m^3. (Photograph from Agriculture, Fisheries and Conservation Department of the Government of Hong Kong Special Administrative Region.)

The responses to this artificial reef-based fishery restoration project were forecast by Pitcher et al. (2002), using three ecosystem and resource models. Information from a variety of local databases and consultations allowed these authors to incorporate (1) diet, growth and mortality data for 255 reef-associated and non-reef fish species, sorted by size, and collected into 27 functional groups, and (2) descriptions of seven sectors of the Hong Kong fishery into ‘‘Ecosim’’ and ‘‘Ecopath’’ models. These provided the basis for dynamic ‘‘Ecospace’’ simulations to predict fishery performance according to fishery sector and habitat. An actual increase of harvest of large reef fish is forecast when artificial reefs are deployed, in contrast to a non-reefs scenario that depicted continuing depletion of the fishery and increase of lower-trophic level organisms. In one situation, the authors forecast a total catch of reef fish of 100 tons per year, including 60 tons of large demersal reef fish.

This early application of ecosystem simulation to artificial reef performance in a coastal fishery/habitat restoration situation has advantages including the capabilities for analysis of trade-offs among marine protected area and reef deployment design practices and for comparison of policy options (Pitcher et al., 2002). Potential concerns include levels of confidence and uncertainty.

Trends in success of habitat restoration

The preceding four case studies were selected because in aggregate they possess attributes useful to planning other marine ecosystem restoration efforts. In contrast with many typical artificial reef deployments that have relatively small areal ‘‘footprints,’’ such as individual ships or ‘‘patch reefs’’ of concrete modules, three of the studies are being implemented on a relatively larger scale, from a 61-ha site in California to regional marine parks in Hong Kong to virtually the entire Chesapeake Bay. Comparison of the preceding project summaries with the 51 steps given in Table 1 indicates the thoroughness of planning and execution of the projects, such as in identifying need for restoration, gathering ecological information, monitoring, etc.

Selected attributes suggested as desirable for marine ecosystem restoration are summarized in Table 2. Each situation includes the measurable objectives necessary to successful implementation of aquatic ecosystem restoration. Both the Chesapeake Bay and San Onofre efforts specify units of oyster biomass (25 g/m^2) and plant density (4/

Table 2 Components for marine ecosystem restoration, as addressed in four situations using artificial reefs

Component of restoration	System			
	Kelp forests	Coral reefs	Oyster reefs	Reef fisheries
Goal/ performance measure	4 plants/100 m^2; monitoring in progress	Increased coral biomass/ structure; monitoring	Oyster biomass = 25 g/m^2; monitoring in progress	Increased fishery yield; monitoring in progress
Ecosystem context	Adjacent natural reefs as reference target and source of recruits	Site-specific	Oysters as critical component of ecosystem to enhance water quality; opportunity for recovery of other habitats (e.g., seagrass)	Considers adjacent natural reefs and open mud and sand
Ecological basis for design	Height, spacing of reefs; predators	Species suited to sites	Physical structure; anoxia events	Species diet, growth
One tool of many used	Kelp transplantation being evaluated	Not considered	Coupled to watershed management	Coupled to management of fishing effort
Advanced techniques	Experimental pilot study to ensure design most likely to attain targets	Compatible substrates for transplants; test hypotheses	Modeling to predict ecosystem benefits; water quality—seagrass linkages	Modeling forecasts of fishery response

100 m^2), respectively, which in fact are derived from historical baseline values. The Hong Kong program is more general in seeking increased fishery catch, and the coral reef situations were smaller but focused in increasing structure. In all cases monitoring to acquire data for measurement of performance is in place. Further, the ecology of organisms has been used to direct design of reef structures, such as in defining height of kelp reefs to minimize both scour by currents and grazing by herbivores.

In three cases, reefs are being used in two broader contexts. As a fishery management tool, for example, they are coupled with new fishing license measures in Hong Kong. In a broader ecosystem context, management of nutrients from the Chesapeake Bay watershed along with oyster reef restoration and protection to enhance filtering are expected to improve water quality and increase opportunity for seagrass bed recovery. The southern California kelp bed project is explicitly quantifying recruitment of kelp, other benthic species, and fishes in a spatially explicit way, cognizant of the importance of the mosaic of surrounding habitats for reference and as a source of recruits. Finally, the use of pilot studies to test reef designs (kelp), ecological modeling to predict reef function (oysters, Hong Kong), and testing of hypotheses (coral) represent effective steps in maximizing success of the projects through rigorous scientific study design.

In conclusion, the technology for marine ecosystem restoration and application of artificial reefs to it are young. As indicated by the case studies above, there is a valid role for artificial reefs in marine ecosystem restorations. Even before reefs can be used in a restoration setting, though, the nature and extent of degradation must first be established, particularly in terms of characterizing and quantifying the pre-existing (baseline) condition. Other solutions that may be more appropriate must be evaluated, ranging from control of pollution or land-use practices to management of the ecosystem. In defining the utility of artificial habitats in restoration, the question of habitat-limitation in the ecosystem must be considered. As discussed by Frid and Clark (1999), scientific knowledge of ecosystems must be integrated with economic and social forces impacting the environment.

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